

## UCAC3: ASTROMETRIC REDUCTIONS

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### ABSTRACT

Presented here are the details of the astrometric reductions from the  $x$ ,  $y$  data to mean right ascension (R.A.), declination (decl.) coordinates of the third U.S. Naval Observatory CCD Astrograph Catalog (UCAC3). For these new reductions we used over 216,000 CCD exposures. The Two-Micron All-Sky Survey (2MASS) data are used extensively to probe for coordinate and coma-like systematic errors in UCAC data mainly caused by the poor charge transfer efficiency of the 4K CCD. Errors up to about 200 mas have been corrected using complex look-up tables handling multiple dependences derived from the residuals. Similarly, field distortions and sub-pixel phase errors have also been evaluated using the residuals with respect to 2MASS. The overall magnitude equation is derived from UCAC calibration field observations alone, independent of external catalogs. Systematic errors of positions at the UCAC observing epoch as presented in UCAC3 are better corrected than in the previous catalogs for most stars. The Tycho-2 catalog is used to obtain final positions on the International Celestial Reference Frame. Residuals of the Tycho-2 reference stars show a small magnitude equation (depending on declination zone) that might be inherent in the Tycho-2 catalog.

*Key words:* astrometry – catalogs – methods: data analysis

### 1. INTRODUCTION

The U.S. Naval Observatory (USNO) CCD Astrograph Catalog (UCAC) project began observations in the Southern Hemisphere at Cerro Tololo Interamerican Observatory (CTIO) in 1998 January. In 2000 October, the first catalog, UCAC1 (Zacharias et al. 2000), was published covering about 80% of the southern sky with positions and preliminary proper motions for over 27 million stars. The Astrograph was moved to the Naval Observatory Flagstaff Station (NOFS) in 2001 October to complete the Northern Hemisphere observing after 2/3 of the sky were completed from CTIO. The second catalog, UCAC2 (Zacharias et al. 2004), was released in 2003 July with the same level of completeness as in UCAC1, but with improved reduction techniques, early epoch plates for improved proper motions and extended sky coverage. All sky coverage for UCAC observations were completed in 2004 October.

The third catalog, UCAC3 (Zacharias et al. 2010), is the first all-sky data release in the UCAC series, containing about 100 million entries with a slightly fainter limiting magnitude than in previous versions. The magnitude range for UCAC3 is roughly 8.0–16.3 mag in the UCAC bandpass (579–642 nm, hereafter UCAC magnitude). A detailed introduction into UCAC3 with comparisons to other catalogs and warnings for the users are given in Zacharias et al. (2010). Any user is also urged to read the extensive “readme” file provided with the DVD release.

The UCAC3 is based on a complete re-reduction of the pixel data aiming at more completeness with the inclusion of double star fitting, problem case investigations, and the slightly deeper limiting magnitude (Zacharias 2010). The final positions are based on the Tycho-2 (Høg et al. 2000) reference frame as in UCAC2. However, Two-Micron All Sky Survey (2MASS; Skrutskie et al. 2006) residuals are used to probe for systematic errors in astrometric reductions as will be explained below.

In UCAC1 and UCAC2, it was shown that the 4K CCD in the astrograph camera has a relatively poor charge transfer efficiency (CTE), leading to coma-like systematic errors in the uncorrected stellar positions. The effect is seen mainly in

the  $x$ -axis (right ascension), which is the direction of the fast readout of charge, while the  $y$ -axis (declination) shows a much smaller effect. In UCAC1 a simple empirical approach was used to correct for this effect with the basic assumption that the effect was linear along the  $x$ -axis and no assumption for a dependence on magnitude. For UCAC2 the empirical approach was extended with a more complex model as a function of  $x$ ,  $y$ , and instrumental magnitude derived from flip observations of calibration fields. Flip observations are obtained by observing the same field with the telescope on one side of the pier (east or west) then repeat with the telescope on the other side. Thus, two images of the same area in the sky are obtained which are rotated by 180° with respect to each other.

In both previous UCAC catalogs sub-pixel phase and field distortion errors also have been investigated. For UCAC1, the pixel phase was modeled with an empirical function showing an amplitude on the order of 12 mas resembling a sine function. For UCAC2 the pixel phase errors were investigated further and found to also be a function of the FWHM of the stellar image profiles. The field distortion pattern (FDP) was modeled in both previous reductions by binning reference star residuals from individual frames used in the reductions.

The new pixel data reductions up to  $x$ ,  $y$  data are described in Zacharias (2010). This paper describes the reductions following the  $x$ ,  $y$  data up to the CCD-based mean R.A. and decl. positions. Early epoch data and procedures to derive proper motions are presented in the UCAC3 release paper (Zacharias et al. 2010), while details about an important part of the early epoch data, the southern proper motion (SPM) data will be given elsewhere (T. Girard et al. 2010, in preparation).

### 2. INPUT DATA

For the astrometric reductions of UCAC3 as described in this paper, two sets of input data are needed: the  $x$ ,  $y$  data from selected CCD observations and reference stars. Here two different reference star catalogs are used for different purposes.

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**Table 1**  
Summary of UCAC Frames<sup>a</sup>

Site/Orientation	Number of Calibration Frames	Number of Survey Frames	Number of Minor Planet Frames	Number of Pluto Frames
CTIO east	1582	5	14	0
	0	3	14	0
CTIO west	1583	163460	828	10
	0	155143	796	0
NOFS east	2452	66940	1340	84
	0	58523	1156	74
NOFS west	1525	2580	32	0
	0	2397	28	0
Total	7142	232985	2214	94
	0	216066	2068	74

**Note.** <sup>a</sup> First row number represents the total number of UCAC frames, while the second row number gives the number of frames used in the final UCAC3 reduction.

### 2.1. CCD Frame Selection

Out of the about 278,000 UCAC frames ever taken, all applicable survey frames, calibration field, and minor planet exposures are selected for the reductions presented here. Poor quality frames are excluded. Quality criteria include limiting magnitude, internal fit precision of high signal-to-noise ratio (S/N) stellar images, and mean image elongation. About 15% of the observations are qualified as “poor” (see also Zacharias et al. 2000). All frames that pass those quality criteria are included. Then the all-sky completeness from the selected data are examined and frames that almost meet the quality criteria are included as needed to provide a complete all-sky coverage.

The final UCAC3 catalog contains mainly the survey frame data. The minor planet observations will be published separately, while the calibration field observations are only used in the first reduction steps to derive corrections to systematic errors. A summary of the CCD observations is given in Table 1. The frames taken along the path of Pluto are included here from a Collaboration with L. Young (SWRI) for occultation predictions.

A total of about 50 fields in the sky observed at about 10–30 different epochs with multiple exposures each time were used as astrometric calibrations. These typically low galactic latitude fields around ICRF targets, equatorial calibration fields, and open clusters were observed about 10–30 times during the project and with the telescope flipped between orientations east and west of the pier to provide a reversal of R.A. and decl. orientation in  $x$ ,  $y$  space. Data from these fields are utilized to derive certain systematic error corrections (see below). However, these frames are not included in the final UCAC3 reductions based on the Tycho-2 reference catalog.

Frames around extragalactic link sources taken with the astrograph at times of deep CCD observations (mostly with the KPNO and CTIO 0.9 m telescopes) are not included here either. These data are still under investigation and a separate paper is in preparation regarding the optical link to ICRF quasars.

### 2.2. $x$ , $y$ Data

For all astrometric reductions described below only the  $x$ ,  $y$  results from pixel data profile fit model five (symmetric Lorentz profile with pre-set  $\alpha$ ,  $\beta$  shape parameters) are used. This fit model has five free parameters per single star image (background, amplitude, center  $x$ ,  $y$ , width of profile), similar to the more familiar two-dimensional Gauss model. However, the Lorentz profile matches the observed point-spread function

**Table 2**  
Number of Reference Star Observations Used for Reductions

Site/Orientation	Number of 2MASS Star Observations	Number of Tycho-2 Star Observations
CTIO east	8772812	1600
CTIO west	203915168	9683015
NOFS east	58493251	4071859
NOFS west	7856501	186557
Total	279037732	13943031

(PSF) of our data significantly better than the Gaussian model. For more details and explicit PSF model functions see the UCAC3 pixel reduction paper (Zacharias 2010).

Double star fits of blended images are based on the same Lorentz image profile model, however three more free parameters are used for the two center coordinates and the amplitude, respectively, of the secondary component. Both the primary and secondary components are fit simultaneously. A single width of the profiles for both components of a double star and a single background level parameter is used in this fit.

The  $x$ ,  $y$  data files also contain internal errors on the center coordinates derived from the least-square fits, two instrumental magnitudes based on the profile fit model and a real aperture photometry, respectively, and several auxiliary flags from the raw pixel reduction step. For more information about the raw data reductions see the UCAC3 pixel reduction paper (Zacharias 2010).

### 2.3. Reference Stars

The 2MASS catalog does not provide proper motions. However, the UCAC and 2MASS observations were made almost at the same epoch and the 2MASS positions are of high quality with random errors of about 70 mas per coordinate for well-exposed stars and small systematic errors (Zacharias et al. 2006). Due to the deep limiting magnitude and high density the 2MASS catalog is an excellent tool to probe UCAC data for systematic errors on a statistical basis, allowing to stack up many residuals as a function of a large number of parameters, as will be described below. Table 2 lists the number of available observations of reference stars, each providing a residual along R.A. ( $x$ ) and decl. ( $y$ ).

For this purpose a subset of the 2MASS point source catalog is constructed. Stars are selected from the Naval Observatory Merged Astrometric Data set (NOMAD) using the 2MASS

identifier and imposing a limit of  $V$  or  $R \leq 16.5$  to select 116,247,341 2MASS stars. For these, the original 2MASS positions are retrieved and matched with UCAC observations on a frame-by-frame basis.

Proper motions of this reference star catalog are taken out of the NOMAD catalog. Even if these are not very accurate for faint stars, they bridge the few years of epoch difference to UCAC data to avoid large-scale biases from galactic dynamics. For most stars in the southern hemisphere, the epoch difference between 2MASS and UCAC is  $\sim \pm 1$  yr, while it gradually increases for stars at higher declinations. Near the north celestial pole the epoch difference is about four years.

The 2MASS data are used only to derive most of the systematic error corrections of the UCAC  $x, y$  data. As with UCAC2, the Tycho-2 catalog is used as the only source for reference stars in a final astrometric reduction to obtain UCAC3 positions on the International Celestial Reference Frame (ICRF). Only stars from the Tycho-2 catalog indicated as having good astrometry have been used for this reduction. Tycho-2 proper motions have been used to propagate the positions to the epoch of the individual UCAC  $x, y$  observations.

Both reference star catalogs are sorted by declination and stored in binary direct access files. For each catalog a match to the  $x, y$  data is performed to produce cross-reference output files per CCD frame containing the record numbers from the  $x, y$  direct access data and the reference star catalog, as well as the magnitude of the star,  $B-V$  color, and astrometry flag (for Tycho-2). This scheme allows a fast runtime for the many passes through all the data to perform the astrometric reductions without the need for a match of reference stars each time.

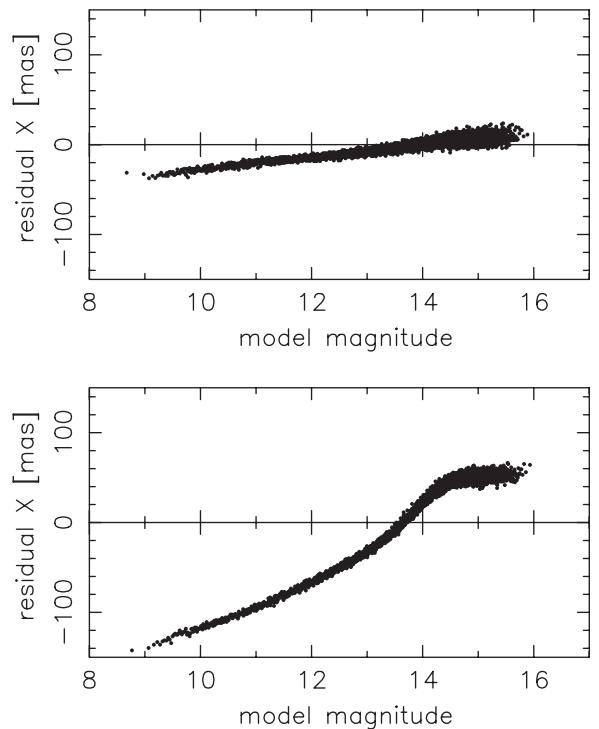
### 3. ASTROMETRIC REDUCTIONS

For the astrometric reductions in UCAC3 extensive systematic error investigations are performed. The largest systematic error is caused by the poor CTE of the detector, followed by geometric field angle distortions. An iterative approach was adopted utilizing 2MASS residuals to determine each of these effects in turn as described below. The idea here is to use an empirical approach as done in the past, but investigate further dependences to better model the effects seen in the 4K CCD pixel data. Preliminary results were presented earlier (Finch et al. 2009). A pure magnitude equation is derived from internal calibration observations only. Finally, the position shifts as a function of the sub-pixel location of an image in the focal plane (the sub-pixel phase error) is derived, however, the  $x, y$  data used for that are the original measures before applying the other corrections.

Systematic position offsets as a function of color and differential color refraction due to Earth's atmosphere are small (about 5 mas) due to the narrow UCAC spectral bandpass. No such corrections are applied for the UCAC3 catalog.

#### 3.1. Preliminary Field Distortion Pattern

In the first step of the astrometric reductions, the CTE caused systematic errors (coma-like) are approximated by a linear model as a function of magnitude and  $x$  pixel coordinate, similar to the CTE modeling of UCAC1. This takes out about 80% of the CTE effect. The pre-corrected  $x, y$  data are then used in a preliminary astrometric reduction with 2MASS reference stars to produce an approximate FDP, i.e., systematic errors purely based on the  $x, y$  location of a stellar image on the area of the detector. Although the coma-like corrections for the CTE effect should not bias the purely geometric FDP corrections, the



**Figure 1.** CTIO west residuals in  $x$  with respect to 2MASS reference stars as a function of UCAC model magnitude using frames taken at 20 s exposures (short). The top plot shows the residuals for low  $x$  near pixel 1 and the bottom plot for high  $x$  near pixel 4094. Each dot represents the mean over 1000 residuals.

scatter in the data is largely reduced by correcting for most of the CTE effect first. This leads to a more accurate FDP as would be generated without applying any CTE corrections.

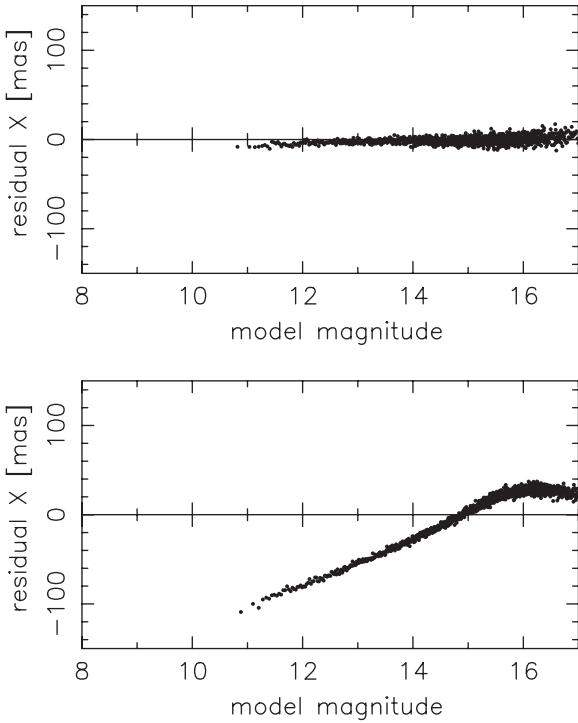
Maximal systematic errors in the FDP are about 24 mas, with typical corrections in the 5–10 mas range. This preliminary FDP is then applied to the otherwise uncorrected  $x, y$  data to analyze the CTE effect from scratch in the following step. The same reasoning applies here; with good FDP correction in hand the scatter of the residuals is reduced to accurately probe the systematic errors induced by the poor CTE.

#### 3.2. CTE Effect

When the CCD reads out an image, the electrons are transferred from pixel to pixel until the charge reaches the output register. The low CTE of the 4K CCD causes charge to be left behind as this transfer occurs, leading to slightly asymmetric images. The amount of asymmetry and the derived  $x, y$  center of stellar images with respect to the unaffected position depend on the  $x$  pixel location, the brightness of the star, the length of the exposure, and other factors.

As found here and in previous UCAC reductions the CTE effect is by far the most substantial systematic error seen in the raw UCAC  $x, y$  data amounting up to about 200 mas. The effect is predominantly seen in the  $x$ -axis along right ascension and increases from no effect near  $x = 0$  pixel to a maximum near  $x = 4094$  pixel, as evident in Figure 1. A similar effect is also seen in the  $y$ -axis, but to a lesser degree because of a slower charge transfer in the direction of declination.

For the reductions, the UCAC frames are separated into individual data sets depending on observation site (CTIO or NOFS) and telescope orientation (east or west). Over 216,000 frames are used for the reductions, see Table 1. Most frames at CTIO were observed with the telescope west of the pier,



**Figure 2.** CTIO west residuals in  $x$  with respect to 2MASS reference stars as a function of UCAC model magnitude using frames taken at 150 s exposures (long). The top plot shows the residuals for low  $x$  near pixel 1 and the bottom plot for high  $x$  near pixel 4094. Each dot represents the mean over 1000 residuals.

while at NOFS the regular observing was performed east of the pier.

Because the instrument had to be disassembled for the move from CTIO to NOFS the camera alignment and other instrument properties are slightly different at both sites. This explains the slightly different patterns for systematic error corrections found for the two sites. However, the 2MASS reference star catalog is dense enough to provide a sufficient number of residuals for statistically significant results even on relatively small subsets of the UCAC data.

For UCAC3 we found that the CTE systematics show a dependence on FWHM, brightness of the star, exposure time, location on the chip ( $x, y$ ), camera orientation (east, west), and observing site (CTIO, NOFS). For example Figures 1 and 2 show the CTE caused different systematic position offsets for the  $x$  coordinate as a function of magnitude for 20 and 150 s exposures, respectively.

The residuals with respect to the 2MASS reference stars are split into two major data sets for investigating the CTE effect, CTIO west, and NOFS east. A plotting program is then used to display and determine empirical corrections to create a complex look-up table. The table is split up into four different FWHM

bins keeping a roughly equal number of frames per bin, with half step magnitude bins ranging from 8 to 16 mag for all standard exposure times of 20–200 s duration, and five bins along the  $x, y$ -axes. Each data set is evaluated and look-up tables are created to correct for the residuals (see sample, Table 3).

For each of the main data sets, CTIO west and NOFS east, tables are created separately for the  $x$ - and  $y$ -axes. After testing we found that these tables could also be used for the data of the other configurations, (CTIO east and NOFS west) corresponding to the observation site. After applying corrections and re-running the residuals the correction tables are continuously updated until the residuals flattened out. The largest correction from the residuals for CTIO is 204 mas in the  $x$ -axis and –32 mas in the  $y$ -axis. For NOFS the largest correction from the residuals is 216 mas in the  $x$ -axis and –67 mas in the  $y$ -axis.

### 3.3. Pure Magnitude Equation

The 2MASS positions are uncorrelated to the  $x, y$  pixel coordinates of the UCAC observations. Thus any systematic errors seen in the 2MASS–UCAC residuals as a function of UCAC  $x, y$  and also as a function of magnitude times these coordinates (coma terms) are inherent in the UCAC data and can be corrected with the above procedure.

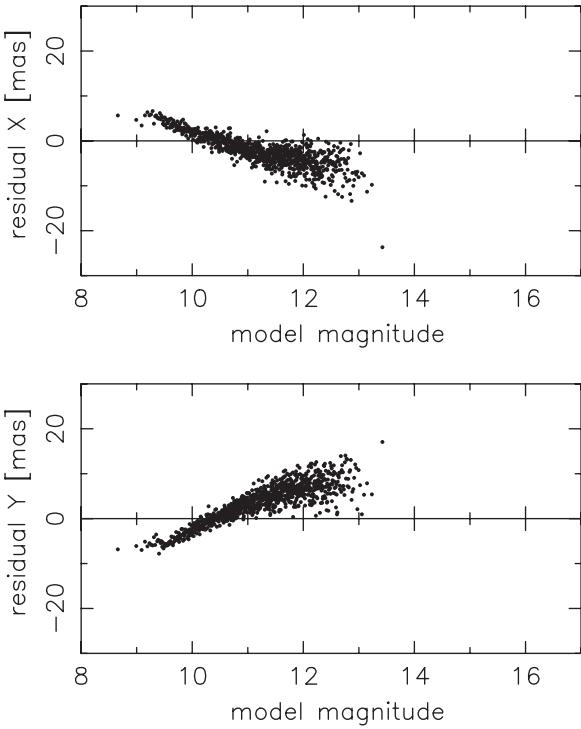
However, this is not the case for a pure magnitude-dependent systematic error, which could originate in either or both catalogs. With the systematic error corrections applied to the UCAC  $x, y$  data as described above any possible pure magnitude equation from 2MASS was transferred into the UCAC positions. Different catalogs have typically different magnitude equations. As an example Figure 3 shows the residuals as function of magnitude from a reduction of UCAC data with Tycho-2 reference stars, after applying all systematic error corrections based on the 2MASS reductions. This clearly shows a difference in magnitude equation between 2MASS (= UCAC system at this point) and Tycho-2 without knowing what the error free positions might be.

The flip observations of calibration fields are used to determine the overall, pure magnitude-dependent systematic errors in the UCAC data independent of any external reference star catalog. With these observations the same field in the sky has been observed with sets of frames rotated by 180° with respect to each other. Any  $x, y$  coordinate offset as a function of magnitude shows up in the residuals of a transformation of east versus west frames  $x, y$  data. We derived overall magnitude equation slope terms for long and short exposure frames and both sites separately. These are then applied globally in the final astrometric reductions.

After applying all corrections a small magnitude term of a few mas mag<sup>–1</sup> is still seen in the residuals of the Tycho-2 reductions of UCAC data as shown in the UCAC3 release paper (Zacharias et al. 2010). This indicates that such a magnitude equation is present in the Tycho-2 catalog itself, which

**Table 3**  
Example CTIO West CTE Lookup Table for Frames Taken at 20 s Exposures with Corrections Given in mas

	8.0 mag	8.5 mag	9.0 mag	9.5 mag	10.0 mag	10.5 mag	11.0 mag	11.5 mag	12.0 mag	12.5 mag	13.0 mag	13.5 mag	14.0 mag	14.5 mag	15.0 mag	15.5 mag	16.0 mag
<i>xbin1</i>	147	148	143	134	119	108	95	81	66	49	33	18	–8	–44	–69	–76	–86
<i>xbin2</i>	116	111	115	111	105	90	80	69	53	42	27	18	–4	–32	–52	–59	–74
<i>xbin3</i>	101	92	95	85	76	67	60	44	41	33	24	14	2	–17	–31	–39	–48
<i>xbin4</i>	68	61	61	59	56	43	38	33	29	23	19	11	2	–10	–17	–21	–30
<i>xbin5</i>	52	47	42	41	43	37	32	28	25	23	17	13	11	3	1	0	–10



**Figure 3.** Residuals in  $x$  (top) and  $y$  (bottom) for CTIO west with respect to Tycho-2 reference stars as a function of UCAC model magnitude. Each dot represents the mean over 3000 residuals.

is found to vary as a function of declination zone as one would expect.

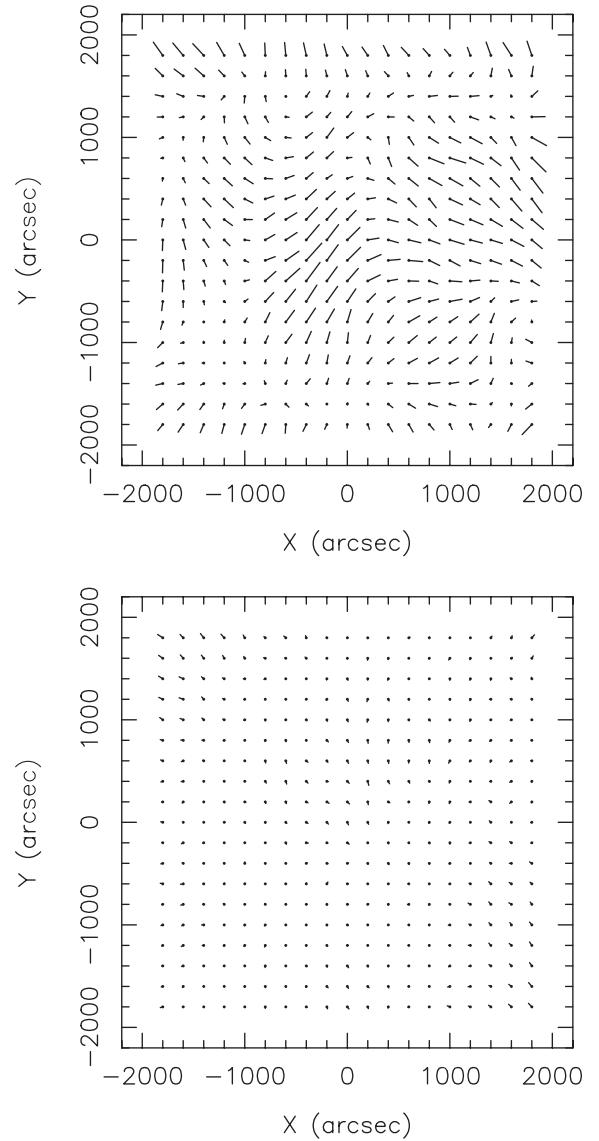
It would be preferable to derive all systematic error corrections from internal calibration observations. However, the flip observations alone do not allow us to do so because of the degeneracy between a pure magnitude equation and coma-like terms. Only after correcting the UCAC  $x$ ,  $y$  data for coordinate-dependent (including coma) terms do the flip observations allow for a unique solution of the magnitude equation. Of course the assumption here is a constant magnitude equation, not changing from exposure to exposure. This assumption cannot easily be made for photographic astrometry, which is affected by a highly nonlinear detector, but should hold better for CCD data.

#### 3.4. Field Distortions

FDPs are derived for UCAC3 by binning thousands of reference star residuals of individual CCD frames using the same procedure as in the previous UCAC reductions. These reductions are performed on the CTE corrected data but without applying the preliminary FDP used before.

From deriving FDPs of various subsets of the data we found that the FDP is almost constant except for a small difference depending on observing site (CTIO or NOFS). Residuals are created using all good survey frames with respect to 2MASS reference stars split into CTIO west and NOFS east data sets. The data using opposite camera orientations than used for most of the observations (i.e., CTIO east and NOFS west) did not have significantly different field distortions so only two correction tables are used for the final reductions. FDP corrections for frames taken with the camera orientation not used frequently are applied by rotating the FDP of the data with the large amount of observations at that site.

Figure 4 (top) shows the FDP for CTIO west with vectors up to 23 mas in length. The FDP for NOFS east is slightly different



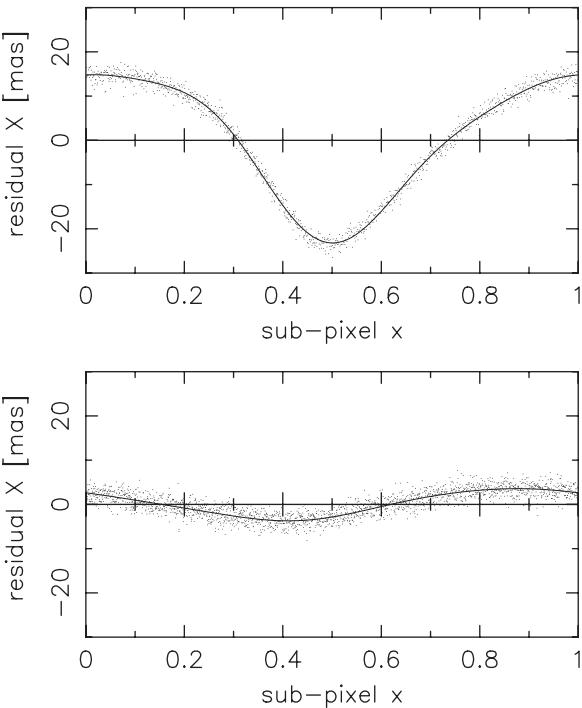
**Figure 4.** FDP plot of 2MASS stacked residuals for CTIO west (top) and the difference between vectors of CTIO west and NOFS east (bottom). The scaling of the vectors is 10,000 which makes the largest corrections for CTIO west (top) 23 mas and the largest difference vector (bottom) 6 mas.

with vectors up to 24 mas at some bins. In Figure 4 (bottom), we show the difference (CTIO west–NOFS east) of the two data sets. Although these differences are small (below 6 mas) they are systematic and well determined. Therefore, we choose to use a separate FDP map to correct the data of each site.

#### 3.5. Subpixel Phase Errors

After the above-mentioned systematic errors have been corrected the 2MASS reference star catalog is used again to generate residuals from all applicable UCAC survey frames. Residuals are analyzed as a function of the original  $x$  and  $y$  pixel coordinate fraction (sub-pixel phase) before other corrections are applied. Various subsets of the data are looked at. Systematic errors are found to be a function of the FWHM of the image profiles. Figure 5 gives some examples. The results are found to be independent of exposure time, as expected. However, a slight difference between the CTIO and NOFS data is found.

The amplitude of the sub-pixel phase-dependent systematic errors in the star positions is shown in Figure 6, here for the



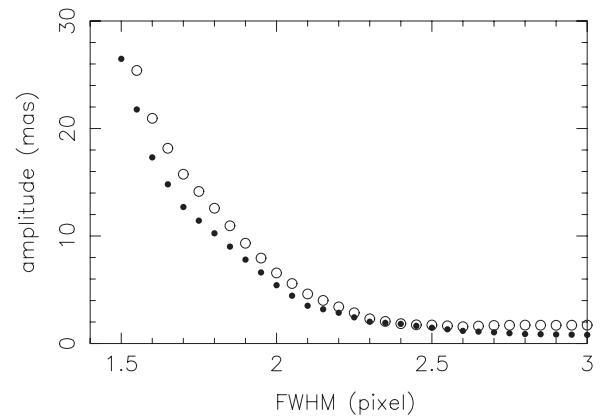
**Figure 5.** CTIO west residuals in  $x$  with respect to 2MASS reference stars as a function of the sub-pixel phase. The top and bottom plots show residuals with an average FWHM of 1.54 and 2.11 pixel, respectively. Each dot represents the mean over 5000 residuals. The fitted curve is from a least-squares adjustment using a model with a total of six Fourier terms.

corrections to the  $x$  coordinate; those for the  $y$  coordinate are somewhat smaller. All sub-pixel phase systematic corrections are smaller than what was found in UCAC2. This is a consequence of using an image profile model in UCAC3 (Lorentz profile) which better fits the true PSF than was the case for UCAC2 (Gauss model).

However, the function of the sub-pixel phase systematic errors is more complex in the UCAC3 than UCAC2 data, where a simple sine and cosine term were sufficient. For the UCAC3 data we had to expand to three sine and three cosine terms in order to fit the sub-pixel phase errors sufficiently well (Figure 5). These six parameters are determined separately for 12 sets of data binned by FWHM (from 1.5 to 3.0 pixels), and split by NOFS and CTIO data. Calibration tables are then generated for equal steps along FWHM by interpolation and  $x$ ,  $y$  corrections applied, separately for each coordinate, based on these tables.

#### 4. MEAN POSITIONS

Positions of all detected objects are obtained frame-by-frame from a final astrometric reduction with the Tycho-2 reference star catalog and correcting raw  $x$ ,  $y$  data first for the sub-pixel phase errors, then for systematic errors as a function of  $x$ ,  $y$  (FDP), then for mixed terms of coordinate with magnitude (CTE effect), and finally for a pure magnitude equation, as explained above. Apparent places and refraction are corrected rigorously using the Software for Analyzing Astrometric CCD (SAAC) code (Winter 1999), which also utilizes the Naval Observatory Vector Astrometry Subroutines (NOVAS) code (Kaplan 1989).<sup>1</sup> The thus obtained positions are on the ICRF at the individual



**Figure 6.** Amplitude of the sub-pixel phase-dependent positional correction as a function of image profile width (FWHM) for the CCD astrograph frames taken at CTIO (filled) and NOFS (open circles), respectively.

epoch of each CCD frame (between 1998 and 2004) and are output to FPOS (final position) files.

Previously identified and flagged observations of minor planets and high proper motion stars are output to separate files. All other individual positions are output by declination zones and then sorted by declination. Weighted mean positions are calculated from the individual images of each star, generating a running star number, MPOS (mean position file) on the fly. Over 139 million objects are identified at this step.

All MPOS entries are then matched with early epoch star catalogs and another, more comprehensive 2MASS extract containing about 338 million objects. These 2MASS stars are selected directly from the 2MASS point source catalog without going through NOMAD. The  $R$  magnitude was estimated based on the 2MASS near-infrared  $J-K$  color and stars with  $R \leq 17.0$  or  $J \leq 15.5$  are selected. The unique identifier for stars matched across catalogs is the MPOS star number. Individual early epoch positions are output together with MPOS entries (CCD epoch observations) and sorted by MPOS number. Weighted proper motions and mean positions are then calculated to obtain the UCAC3 release catalog data (Zacharias et al. 2010). Objects that either did not have a reasonable proper motion determined or could not be matched with 2MASS are dropped at this point. Only these compiled catalog mean positions and proper motions are published in UCAC3, not the MPOS or FPOS data, which likely will be made available for the final UCAC4 release after further updates.

#### 5. COMPARISON WITH HIPPARCOS

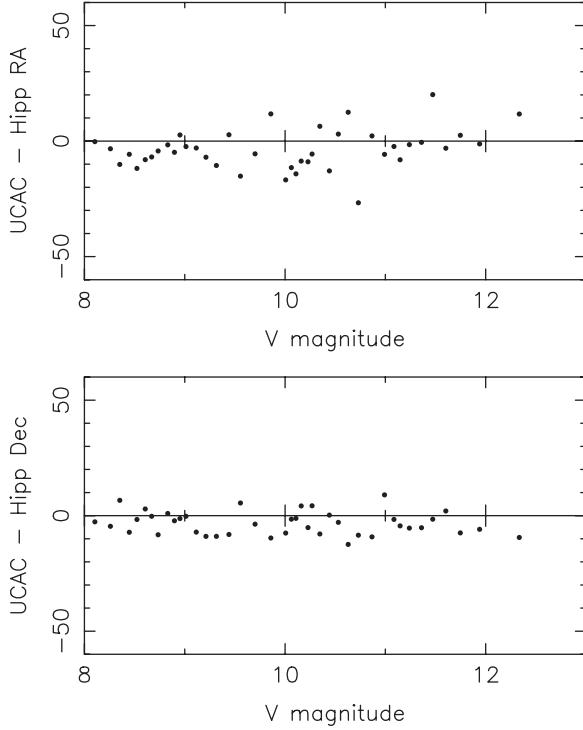
A total of 1510 Hipparcos stars in the 8–12 mag range are randomly selected (about 300 all sky per magnitude interval) and flagged in the UCAC data. These stars are not used as reference stars in test reductions using Tycho-2 reference stars. Thus, the obtained positions are field star positions from UCAC observations independent of the Hipparcos and Tycho catalog positions. Individual UCAC observed positions are then compared to the original (ESA 1997) and new Hipparcos reductions (van Leeuwen 2007) at the epoch of UCAC observations, using Hipparcos mean positions, proper motions, and parallaxes.

After excluding outliers ( $\geq 200$  mas position difference in either coordinate), rms values over observations in each bin are calculated (Table 4). Similarly sorting all observations by magnitude or color, respectively, and binning over 100 observations lead to the plots shown in Figures 7 and 8.

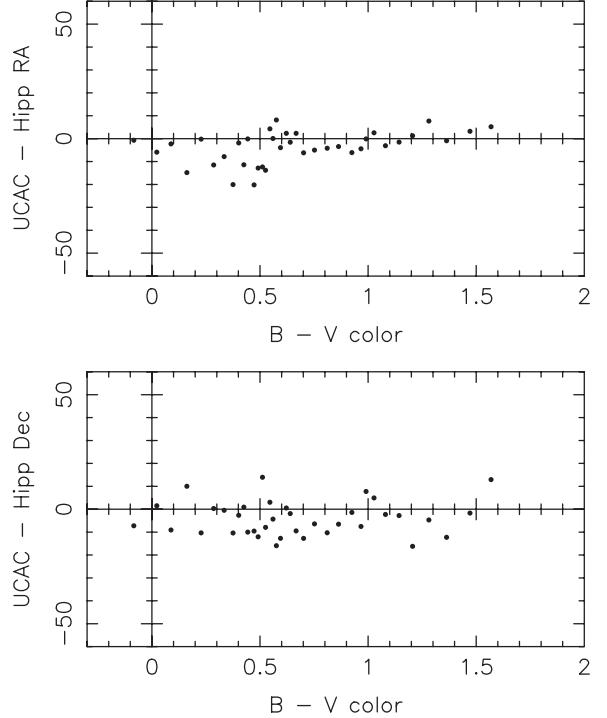
<sup>1</sup> <http://www.usno.navy.mil/USNO/astromonical-applications/software-products/novas>

**Table 4**  
RMS Position Differences and Expected Errors of Observed UCAC3–Hipparcos Positions

Number	$V_{\text{mag}}$ Range Observations (mag)	Difference R.A. Decl. (mas) (mas)	Hipparcos Error R.A. Decl. (mas) (mas)	UCAC3 Error R.A. Decl. (mas) (mas)	Combined Error R.A. Decl. (mas) (mas)	Ratio R.A. Decl. (diff/c.err)
Hipparcos (original)						
423	8.0–8.5	41.946.3	10.78.8	46.947.1	48.147.9	0.870.97
717	8.5–9.0	45.241.9	12.711.7	47.848.0	49.449.4	0.920.85
802	9.0–10.0	43.644.6	21.818.3	47.347.6	52.151.0	0.840.88
1227	10.0–11.0	45.645.5	28.322.5	43.343.9	51.749.3	0.880.92
978	11.0–99.0	52.848.2	42.735.7	42.242.7	60.055.6	0.880.87
Hipparcos (new reduction)						
423	8.0–8.5	42.345.8	8.97.3	46.947.1	47.747.6	0.890.96
722	8.5–9.0	46.444.2	12.010.0	47.848.0	49.349.1	0.940.90
801	9.0–10.0	45.342.6	14.011.6	47.347.5	49.348.9	0.920.87
1238	10.0–11.0	47.444.1	20.816.9	43.443.9	48.147.1	0.990.94
993	11.0–99.0	52.349.9	36.727.5	42.242.8	56.050.9	0.930.98



**Figure 7.** Position differences UCAC–Hipparcos (new reductions) as a function of  $V$  magnitude of a random sample of Hipparcos stars reduced as field stars in UCAC processing. Each dot is the mean of 100 individual UCAC observations.



**Figure 8.** Position differences UCAC–Hipparcos (new reductions) as a function of  $B-V$  color of a random sample of Hipparcos stars reduced as field stars in UCAC processing. Each dot is the mean of 100 individual UCAC observations.

The expected position errors from UCAC3 and Hipparcos data at the epoch of our UCAC observations are also presented in Table 4 together with the expected rms of the combined error and the ratio of expected to observed scatter, separately for each coordinate. In all cases the observed errors (from the scatter of the UCAC3–Hipparcos position differences) are slightly smaller than the expected errors as calculated from the combined formal errors for the same observations, thus at least some of these are overestimated (see also Section 6).

UCAC position differences of those sampled Hipparcos stars do not show systematic errors as a function of magnitude or color exceeding about 10 mas over the range sampled. Plots with respect to the original or new Hipparcos catalog are almost identical.

However, 23 Hipparcos stars (1.5% of this sample) show very large differences (between 300 and 600 mas in either coordinate) when comparing the new reduction Hipparcos positions with the UCAC3 positions at UCAC epoch. A similar number of stars are found when comparing with the original Hipparcos Catalog; however, for not exactly the same stars. All possible combinations of inconsistencies between the two Hipparcos solutions and UCAC data are found, with two of the three positions or all three separated by several standard errors of their internal errors.

## 6. DISCUSSION

The use of an image profile model better matching the actual PSF than a Gaussian model is essential for the astrometric

reductions of blended images. A better matching model also does reduce the amplitude of the sub-pixel phase error and is advisable to be used when no such corrections are being applied to the data. In particular, a comparison of Figure 6 with a similar figure of the UCAC2 paper shows that with a Gaussian model and 2.0 pixel/FWHM sampling the pixel phase error has an amplitude of 11 mas, while with the image profile model 5 as used in UCAC3 this amplitude is only about 6 mas.

The use of such a PSF profile model (still with the same number of fit parameters per star as the traditional Gaussian model) allows us to neglect positional errors as a function of the sub-pixel phase completely for a sampling of about 2.5 pixel/FWHM or larger without the need to investigate possible other dependencies of this systematic error as a function of other things. However, for single stars and with calibration data in hand to correct for the position offsets caused by a sub-pixel phase dependence, the use of a more sophisticated image profile model than a Gaussian might not have an apparent advantage for astrometric reductions.

The slight difference in amplitude of the sub-pixel phase corrections between CTIO and NOFS data is surprising. It could be caused by a slightly different, observed PSF between the two sites, even for the same seeing (FWHM). Whether this is caused by differences in the instrument, guiding or atmosphere is currently not known.

The small systematic errors of UCAC based positions of randomly selected Hipparcos stars confirm the good correction of UCAC3 epoch positions as a function of magnitude and color, at least for the 8–12 mag range. With UCAC3 positions agreeing with Hipparcos data the magnitude equation seen in residuals with respect to Tycho-2 is an indication for such small systematic errors in the Tycho-2 catalog. These are likely introduced through the proper motions, thus the early epoch, ground-based data, as also indicated in the UCAC3 release paper.

The random errors in the observed UCAC–Hipparcos position differences are even slightly smaller than the expected, combined formal errors. For the new Hipparcos reductions the difference is only a few percent, while for the comparison with the original Hipparcos Catalog data the observed errors are about 10% smaller than expected. This indicates a slightly overestimated error in the original Hipparcos Catalog proper motions. The formal position errors for the individual UCAC observations do include the formal image profile fit error, and the conventional plate adjustment error propagation. The weighting scheme used

in this individual CCD frame least-square adjustments also includes an estimated error contribution from the turbulence in the atmosphere, scaled by the exposure time. The mismatch between the actual PSF and the image profile model can lead to an overestimation of the center position errors, particularly for stars as bright as this sample of Hipparcos stars, which would explain the slightly smaller than expected scatter in the Hipparcos to UCAC position differences. The exclusion of outliers at an arbitrary limit of 200 mas could be another possible explanation. At the faint end of Hipparcos (11th magnitude) the Hipparcos catalog positions are of comparable precision to typical mean UCAC positions (based on four images) at their about 2000 epochs. The next step after UCAC, the USNO Robotic Astrometric Telescope (URAT) program (Zacharias 2008) to begin in 2010 thus will likely be capable of improving proper motions of individual Hipparcos stars significantly.

The entire UCAC team is thanked for making this all-sky survey a reality. For more detailed information about “who is who” in the UCAC project the reader is referred to the UCAC3 release paper. The California Institute of Technology is acknowledged for the *pgplot* software. More information about this project is available at <http://www.usno.navy.mil/usno/astrometry/>.

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